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Multi-Criteria Assembly Line Design under Demand Uncertainty

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Abstract

Assembly line design methodologies have been extensively researched during the past decades. Various definitions of problems have been established together with different approaches as to the way they are solved. However, in the automotive industry, most companies still use simple tools and methods for the solution of these problems. There can be spreadsheet applications and simulation tools that do not provide actual decision support, and are limited to assisting engineers in distributing the processes to different work centres. Furthermore, most approaches take into account only a few goals and constraints, by providing either non-realistic solutions or no decision support to production engineers, beyond the distribution of processes. This paper proposes an assembly design algorithm that considers both time and cost parameters for the generation of different line alternatives; the algorithm, taking into account industrial requirements, considers multiple products of several demand profiles in the same line in order to provide support for multi-variant or multi-product systems. Finally, a series of possible alternative configurations of processes are taken into consideration so as to integrate the balancing of the line with process design and equipment specification.

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Keywords: Assembly line design; Multi-objective; Alternative process configuration

1. Introduction

The manufacturing systems include production environments, where materials are processed and individual parts or components are made, along with the facilities where they are joined together in a subassembly or final product. The latter includes all types of assembly systems [1]. One of the main objectives in the process of designing assembly lines is the maximization of the ratio between throughput and the required costs. This is often deemed as a problem of considerable industrial importance [2]. One of the most relevant problems that has been widely researched is the Assembly Line Balancing Problem (ALBP). In the ALBP, an assembly line consists of stations arranged along a conveyor or transportation system, where the jobs are consecutively launched down the line and are transferred from one station to the next. In today's highly competitive market, it is often necessary that engineers design and deploy flexible, user-friendly decision support systems that may be applied to real-world assembly line design problems [3]. At the same time, the production planning of manufacturing systems, including assembly lines, has become one of the key areas of the production systems' research. The production plans have to cope with market, production and logistics uncertainty. The uncertainty of demand, in particular, has been a significant issue for enterprises under the increasing competitive pressure in the global marketplace [4].

2. Assembly line design

Today's manufacturing organizations usually offer diverse product personalization and customization options, in order for the customers' needs to be better fulfilled. This offering of customization options may often lead to significant competitive advantages [1]. However, broad product customization makes the production planning process increasingly complex, since any changes taking place in the

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demand profile may considerably affect the production settings and configurations.

This is one of the main reasons why the design of an assembly line is usually carried out in a series of discrete, consecutive phases. The demand profile is often considered fixed for the subsequent line design phases, such as the one related to the ALBP. The ALBP, in particular, addresses only a subset of the entire line design problem and deals with the way that the required processes for the assembly of a production item, can be efficiently assigned to the various resources (work centres). Throughout the years, numerous methods have been developed and proposed in order to provide solutions to the different forms of ALBPs. The assembly lines can be classified into three main categories with respect to the number of product models they produce; simple (SALBP), mixed-model (MMALBP), where various models of a generic product are produced on the line, in an intermixed situation, and multi (MuMALBP), where more than one product is produced on the line in batches [5].

According to the adopted classification, different approaches for optimization can be assumed (Fig. 1).

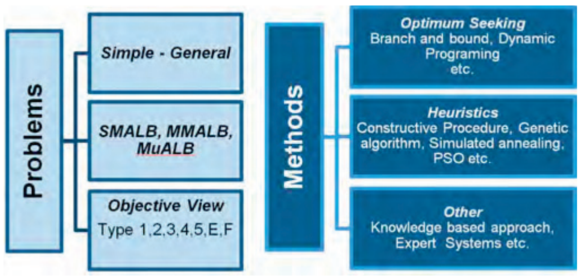

Fig. 1. Assembly Line Balancing Problem and solution methods classification.

A simple ALBP is presented in Fig. 2. A seven-task simple ALBP (SALBP) is presented in the form of a precedence graph. The numbers inside the nodes represent the task identification, while the ones outside the nodes correspond to the processing times. The fourth processing task is, for instance, a 5-time unit. The precedence constraints are represented by arcs, in which case, the second and third tasks have to be completed before the fourth task begins. One of the ways of minimizing the cycling time problem of this assembly line, in 3 word centres, depicted with dashed boxes, is by grouping the tasks as shown in Fig. 2, in work centres. In this example, the cycle time of WC1, WC2 and WC3 are 7, 7 and 8 time units respectively, and therefore, the cycle time for the entire assembly line is 8 time units.

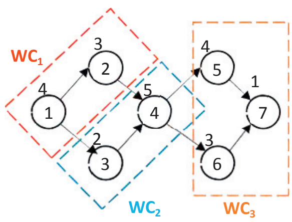

Fig. 2. Simple ALBP example solution.

The consideration of uncertain demand in the process of designing assembly lines has been an important issue of many manufacturing firms. However, there is no simple way of addressing this challenge. In reality, demand uncertainty is quite often a fact that needs to be addressed within the boundaries of flexible assembly lines, which should in turn, be capable of delivering the requested quantities in a cost efficient and timely manner. In essence, this problem is being interpreted as the modelling and optimization of an assembly line's configuration, by addressing, at the same time, the problem of scheduling the line.

3. Assembly line balancing under demand uncertainty

The most studied instance of the ALBP family of problems is the Simple Assembly Line Balancing (SALBP) as described in [8]. The Simple Assembly Line Balancing is a label on the field of research with numerous simplifying assumptions that underlie the definition of an ALBP. A recent study related to demand uncertainty on SALBP is the robust optimization approach proposed in [9]. In this definition of SALBP, the exact quantity of products to be manufactured is unknown. The objective is that the workload variance over all the stations in the line be minimized. To this effect, there are two ways of solving the problem: by using a min–max indicator, which minimizes the maximum workload variance (distributing the workload as evenly as possible) and by considering the so called α-worst approach. Another way of considering uncertainty in ALBP is by assuming that the processing times are uncertain and not deterministic. A related stability study has been performed for the case of the General Assembly Line Balancing Problem (GALBP) [10]; the GALBP covers a series of extensions of the SALBP by integrating elements met in industrial practice, such as U-shaped lines, parallel stations or processing alternatives. The level of demand uncertainty was expressed in [10] via its Mean Absolute Percentage Deviation (MAPD) and the performance of the assembly system was measured by a fill rate. This arrangement was proposed on the basis of the direct influence of demand uncertainty on the so-called fill rate for customer demand. The larger the demand variability was, the more sensitive the fill rate was.

The assembly lines are commonly balanced for the production of mixed products, even slightly different, whilst the demand is usually not fixed and furthermore, each individual customer generally desires not only a specific quantity at a certain time, but also with specific characteristics depending on his / her needs. A change in demand, in the assembly lines that are set to produce mixed or multi-variant products, in a given sequence, would cause a change in the actual operation times of the required processes [11]. This would lead to a re-balancing of the line which would mean production losses for the enterprise, as all resources would have to comply with new processes within the station.

A Mixed-Model Assembly Line Problem (MMALBP) is regarded as being much closer to the industrial assembly line design problems, and may consider a series of uncertain factors, with greater accuracy, as described in [12]. MMALBP may also consider demand variation, since it allows the production of different models on a common base product in an assembly line.

4. Proposed Methodology

In industrial practice, the assembly line balancing phase is often carried out with the consideration of static demand profiles with low or no uncertainty. The main challenge this paper addresses is to take uncertain demand into consideration, during the phase of the assembly line design and not later on when the operation of the assembly line begins. In other words, the assembly line will have to be flexible enough during operation, so that it can cope with demand uncertainty and fluctuations. In the assembly line design phase, it is important to consider the possible products or variants to be produced. During the operation of the assembly line, the demand per product and variant may follow different trends in time.

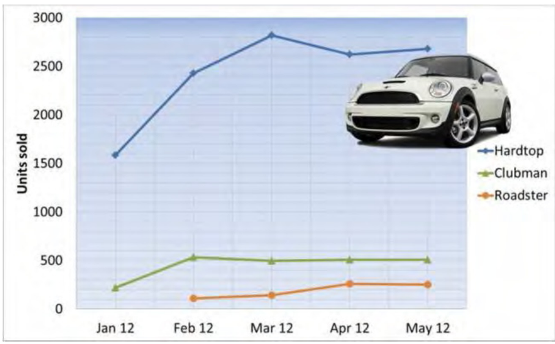

Fig. 3. Mini cooper USA sales between January-May 2012 [13].

For instance, Fig. 3 shows the sales of several variants of a single car model in the USA between the months of January and May 2012; it can be observed that the demand profile of the main variant is quite different when compared with the rest. Moreover, one of the variants has been introduced since February 2012.

In this paper, we propose the usage of a particle swarm optimization algorithm (PSO) for the generation of solutions, which are then evaluated through the application of different demand profiles. The core parts of the approach of [14] were modified and further extended for taking into account more assembly line parameters and constraints, as well as uncertain demand profiles and multiple, often conflicting criteria, such as Cycle Time and Cost. In principle, the main advantage of a PSO algorithm is that it can be used, with slight variations for a wide range of applications or systems for one problem definition. Moreover, there are only a few parameters to be adjusted. As proven through a series of experiments, it can lead to good solutions, not necessarily the optimum ones, in reasonable computational time. At the same time, the proposed PSO could also be part of a hybrid algorithm with more optimization methods, which could be more efficient in cases where assembly lines can be heavily modified [14-17]. The outline of the proposed algorithm is depicted in Fig. 4. It can be further complemented with supply, maintenance and adjustment actions and may also be integrated with various monitoring systems and knowledge bases. The algorithm is designed in a way that it can be executed numerous times in order to evaluate alternative settings regarding both product demand and system behaviour.

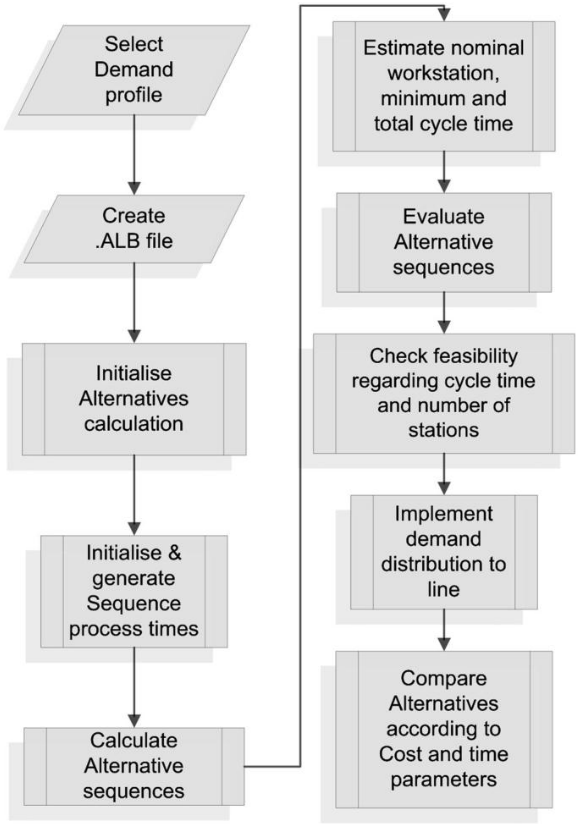

Fig. 4. Main steps of proposed algorithm.

The user can adjust the parameters and can also configure the demand profiles per product / variant. In this fashion, the marketing and sales department may be involved in the process of the assembly line design. For instance, what-if scenarios introducing new products / variants, in specific points of time, may be tested and evaluated.

5. Implementation

The proposed algorithm is implemented as a standalone software module, which may be integrated with other external systems. The input data have been formalized as a standard ".ALB" file, the structure of which has already been defined in literature [18]. This software module reads and analyses the input data and then generates a number of alternative assembly line configurations. The maximum number of alternatives is user-defined. These alternatives are then evaluated against a series of Performance Indicators, such as Cycle Time, Total Investment Cost, Running Cost, etc. Different demand profiles are taken into consideration, whilst also assuming different statistical distributions for the representation of operation times.

5.1. Generation of Alternatives

Whenever a new alternative is generated, the variables that are used for representing times and costs are initialized for all processes. For each alternative, every process is then associated with a randomly generated number, which in turn, represents its priority. The algorithm takes into account the constraints of linked processes, i.e. processes that should definitely be carried out in the same work centre as well as the constraints representing the incompatible processes, i.e. the processes that may not be processed in the same work centre.

5.2. Process sequence generation

For each alternative, a sequence of processes is generated, taking into account all constraints, such as preconditions (processes that have to be completed before a process begins), as well as linked and incompatible processes. It is assumed that the processing time for each process is known (tj) and that each process may be dispatched only in one work centre. As described in the previous paragraphs, the processes are partially ordered by precedence relations, which may be modelled with a precedence graph, where an edge (i, j) denotes that process i should finished before process j can start. The process sequence generation has the following input and output:

- Input: Processes as part of a precedence diagram, along with process times, costs and linked / incompatible processes. For each process, there might be alternative configurations (with different time and cost parameters).
- Output: A feasible process sequence PS.

The process sequence generation follows an iterative procedure. For each alternative, a feasible process sequence is generated, which in the end contains all (N) processes in the form of a linked list. The sequence (list) is constructed iteratively, with the addition of one process at a time. This process is the one having the highest priority from all other processes that can be selected in this position of the linked list. In principle, a process i can be placed in position k ($0 < k < N+1$) in the linked list, only when all predecessors of process i have already been placed in the previous k-1 positions.

Since feasible process sequences have been generated, the next step has to do with the assignment of the processes to the work centres.

5.3. Process assignment

Each alternative contains a generated sequence of processes, which will have to be distributed to the work centres of the assembly line, following an iterative process, which is based on the assignment method, proposed in [19]. Furthermore, each sequence's minimum possible cycle time is calculated together with the associated variances and standard running costs. In case the cycle time of the assembly line is given, the major objective of the algorithm suggests a solution with a minimum number of work centres. When the number of work centres is fixed, one of the major objectives is to come up with a solution with a minimal cycling time. The alternative task sequences are calculated using a PSO-based algorithm. This algorithm maintains a series of alternative solutions (particles), which move iteratively through the search space. The way each particle moves is influenced not only by its local best known position but also by the best known positions. Their position is continuously updated, as particles reach at better ones in the search-space. This is expected to move the alternatives (swarm) towards better solutions.

The number of alternatives (particles) generated by the algorithm is equal to the number of processes. In general, the alternatives are compared against cycle time, standard running cost and feasibility. The best alternative is the resulting output of the program.

5.4. Demand profiles

The fundamental element employed by this algorithm is the demand profile set by the user. Based on most of the recent approaches we base demand profiles on the Compound Poisson Distribution (CPD) [20, 21]. CPD has been extensively researched and is considered as the most realistic approach regarding Assemble-to-Order systems. From a modelling perspective, the Compound Poisson process may also model the demand in the context of fast moving items by considering very low demand time intervals or equivalently a high Poisson rate. Although normal distributions have also been employed in literature, there is no stochasticity incorporated, a fact that can result in a system's less realistic behaviours. Each demand is treated on a first-come-first-served basis (FCFS), so that demand is directly absorbed by the production system. We assume that the multi-variant lines to be balanced require no additional setup time among the different variants. This is true for most final assembly lines where manual processes do not entail any re-configurations. In addition, based on interviews with a production system's integrator, we assume that there is one cycle time per line, meaning that this cycle time should be considered for all variants of the product that is processed. This allows for different variants to be processed on the same line at the same time.

In this group of experiments, we consider a demand profile generated by applying a CPD throughout a working year. Based on the current standard in Europe, we consider that there are 254 working days per year and each day has three 8 h shifts (minus 1-1.5 hours of breaks and non-productive activities per shift). The variants enter the system randomly.

A series of cost elements, such as standard cost per day representing worker wages, energy costs, and a variable cost, which is linearly linked to the process times, corresponding to each variant, have been considered. The latter costs represent additional energy consumed by the equipment per time, machine consumables etc. (Fig. 5).

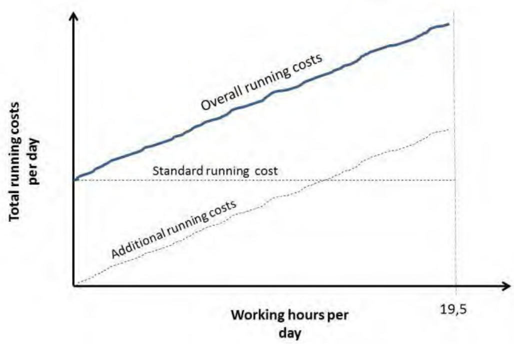

Fig. 5. Running costs per day.

The process times and costs derive from the ALB file and are assumed to be having small variations per produced unit. As mentioned earlier, we consider each day to have 19.5 working hours on average for production activities.

6. Case Study

The algorithm was applied to a case that involved an automotive assembly line with two car engines having 19 and 33 processes respectively. The main constraints were:

- Cycle time: 81 seconds
- Maximum station number: 10 stations
- Yearly running costs: €50,000,000

The constraints were extracted from a similar case of an existing multi-variant line. The data for the processes were taken from an existing assembly line of engines together with the constraints. The costs were estimated on the basis of the feedback of engineers and the values regarding wages etc. are within the average of the existing observations in Europe. It should be noted, that the financial figures presented in the case are indicative since they were altered in order for the confidentiality of certain non-public stakeholders to be maintained.

The processes that are incorporated include precedence relations, sequence dependent time increments (linked or incompatible processes) and alternative configurations of processes, resulting in different durations. The experiments that were carried out are based on two different CPD demand profiles for the two variants. Both demand profiles were defined for a year time span (Table 1).

Table 1: Yearly demands of engine variants for the two cases examined.

	Engine A (units p.a.)	Engine B (units p.a.)
Case #1	50.000	25.000
Case #2	60.000	30.000

The following graphs show the demands generated with CPD, and specifically, the peaks of the demands for a whole year. The CPD is based on the yearly requested capacity, and different values were generated for both products each day.

Based on the initial constraints, the experiments were conducted for maximum cycle times of 79, 80 and 81 seconds. Further to that, the maximum number of stations was initially set to 10 and then to 9. All results had different workloads per station; this was due to the different sequences of processes being selected as an optimal solution and to the selection of different process configurations, with various durations and costs for the same process.

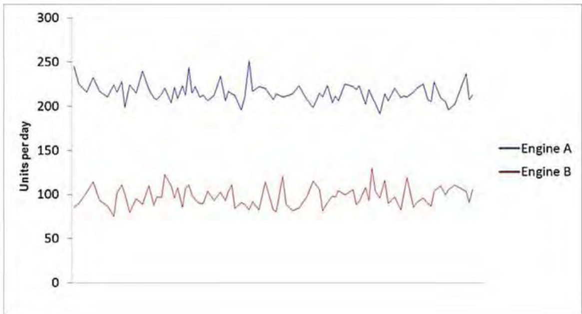

Fig. 6. Demand profile generated for Case #1.

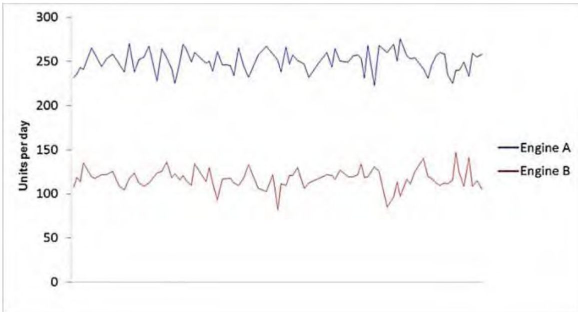

Fig. 7. Demand profile generated for Case #2.

Based on the demand profiles previously described, the running costs for a whole year were calculated as shown in Table 2.

Table 2: Results of the ALB algorithm regarding running costs for the two different cases.

	Cycle time	No. of Stations	Yearly running costs for Case #1	Yearly running costs for Case #2
Alt. #1	79	9	$48.38 * 10^6$	$57.02 * 10^6$
Alt. #2	80	9	$48.38 * 10^6$	$57.02 * 10^6$
Alt. #3	81	9	$48.99 * 10^6$	$57.74 * 10^6$
Alt. #4	79	10	$48.99 * 10^6$	$57.74 * 10^6$
Alt. #5	80	10	$49.61 * 10^6$	$58.46 * 10^6$
Alt. #6	81	10	$49.61 * 10^6$	$58.46 * 10^6$

The results showed that all the alternatives for case #2 had higher costs than the limit initially set. Given the constraints regarding yearly running costs, the capacity of the line seems to be high enough for Case #1, whilst Case #2 seems to exceed the yearly running cost limit. However, since for Case

#1, all the alternatives provided acceptable results, it is up to the production engineer to select one of them, depending on the existence of further constraints regarding tools selected and other production environment details (space, energy requirements, etc.). From the generated alternatives, it is evident that the best solution for Case #1 would be Alternative #1 (Fig. 8), since it respects all constraints and provides the lowest cycle time also for Case #2, an further allocation of at least 7.000.000 would be necessary to meet the additional demand.

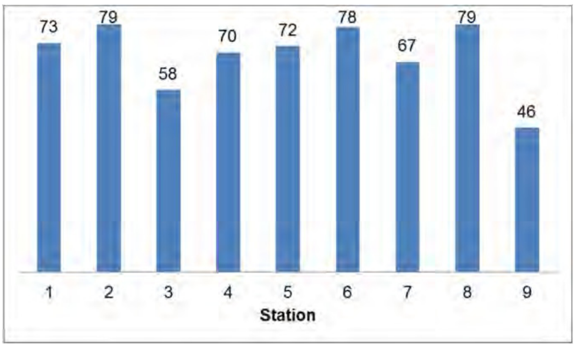

Fig. 8. Workload per station in seconds for the first alternative generated for Case #1.

7. Conclusions

This paper presents an approach for the assembly line balancing problem under different demand profiles and production constraints. A heuristic method, namely, a particle swarm optimization (PSO) based algorithm, has been adopted in this study. The PSO algorithm provides an optimization method with relatively low complexity and high level of adaptability to various constraints. In addition, this algorithm has low processing requirements, thus enabling its usage in various computer systems. The required computing time for all experiments presented is less than a minute, which enables engineers to have a fast feedback and experiment with what-if scenarios. Moreover, since the PSO algorithm considers different demand profiles and production constraints and may calculate alternative sequences under those constraints, it is capable of providing more realistic results, in real time, respecting modern production requirements. The overall setup of the experiments shows the way that the assembly line balancing phase, currently addressed as a static procedure during the design of a line, may well be treated as a dynamic phase, covering different product lifecycle phases, including the design of the line as well as its deployment.

The key advantage of the proposed approach is that the production engineers are provided with flexible choices, concerning the adoption of different work centres' operating sequences and fulfilling different demand profiles, which result in a flexible assembly line with effective performance. In future, the upgrading of the main algorithm for the consideration of supply logistics, inventory information, planned maintenance and breakdown will improve the overall capabilities of the proposed system, by addressing the needs of real assembly systems in a more realistic manner.

As far as the technical approach is concerned, a possible deployment of the methodology as a cloud-based application (software as a service), will dramatically enhance the collaboration of the engineers involved in production design, whilst, at the same time, reduce their time spent on communicating the results. This could in principle be accomplished with the use of a central database for the storage and management of information, related to manufacturing and assembly processes and will allow the connection of an ALB engine to other tools, such as discrete event simulators; will provide more accurate and up-to-date results, and support the decision making process for production and assembly engineers.

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